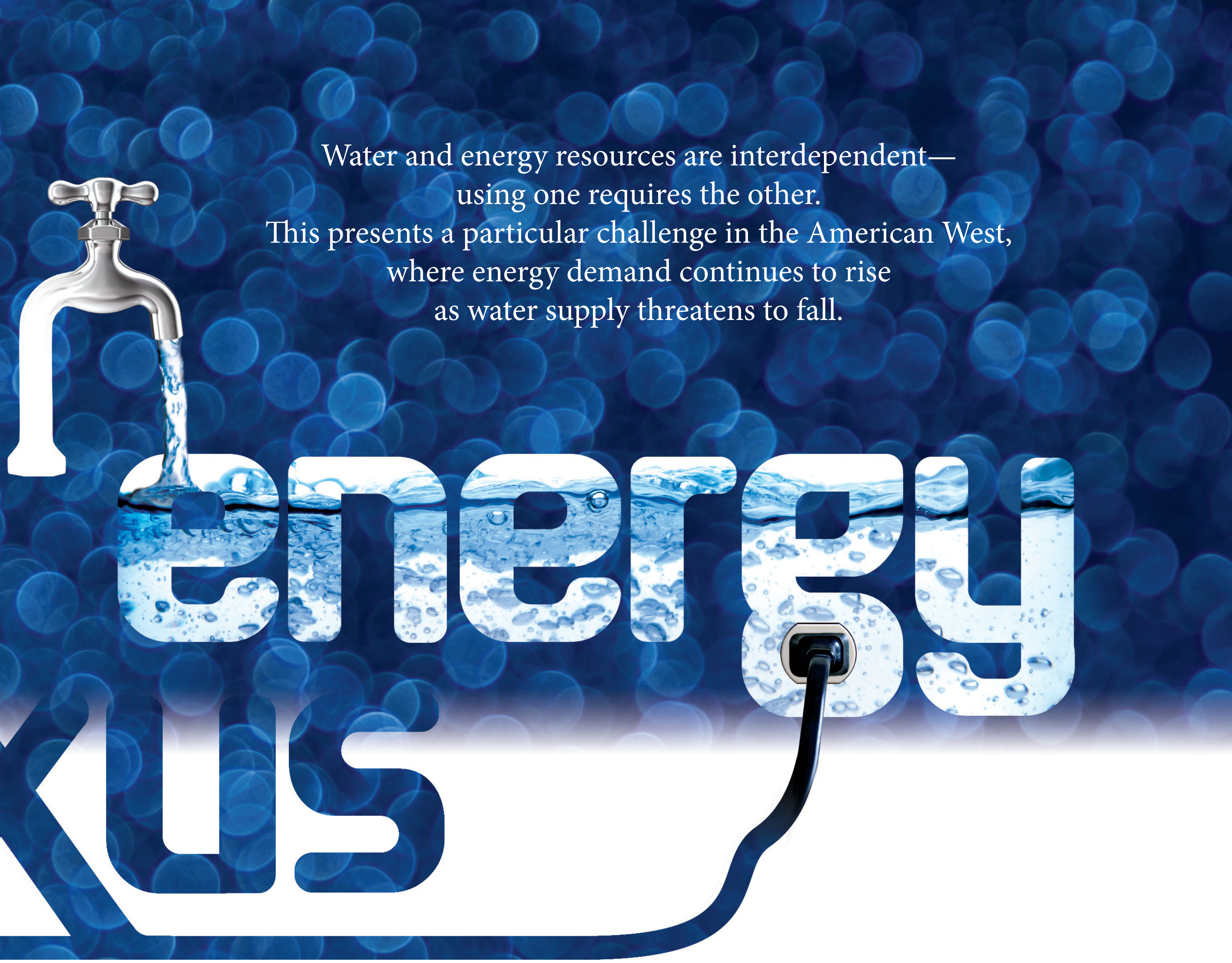
California's mountains have risen by as much as 1.5 centimeters since early 2013, according to sensitive GPS measurements analyzed by the Scripps Institute of Oceanography. The cause? It's not due to increased magma pressure from deep underground or anything of that ilk; it's due to an exceptionally severe drought that spans California and much of the western United States. The drought means less water weighing down the land, and as a result, the West has risen by an amount that lines up with the amount of water lost during the rise—240 gigatons, or roughly the amount that melts from the entire Greenland ice sheet each year.

At the same time, the Colorado River—which provides drinking water to Los Angeles, San Diego, Phoenix, Tucson, Las Vegas, and more—is showing the effects of a 14-year drought. Its Lake Mead reservoir, America's largest, is now down to about three-eighths capacity, its lowest level since Hoover Dam was constructed in the 1930s. The U.S. Bureau of Reclamation predicts that the dam will produce as little as 1120 megawatts of hydropower by mid-2016, despite its 2074-megawatt capacity, due to diminished and oversubscribed river water. And with long-term rising temperatures, reservoir levels are expected to continue to decline because

Water and energy resources are interdependent—
using one requires the other.
This presents a particular challenge in the American West,
where energy demand continues to rise
as water supply threatens to fall.



of increased evaporation and reduced snowfall in the river's Rocky Mountain headwaters.

In all, 40 million Americans depend on the Colorado River's water, as do the farms that produce two-thirds of the nation's winter vegetables. To make up for its shortfall, residents and farmers increasingly draw from underground aquifers, which, for many aquifers in the West, do not recharge nearly fast enough to recover during a human lifetime. NASA satellite measurements confirm that water is rapidly depleting from the Colorado River Basin aquifer spanning western Colorado and eastern Utah, most of Arizona, and parts of California, New Mexico, Nevada, and Wyoming. No one knows exactly how much of its water remains. Yet back in California, farmers are currently withdrawing 62 percent more groundwater than usual—enough in 2014 alone to submerge Washington, D.C., under 90 meters of water.

The predicament does not end with agriculture and public water use. Energy production, broadly speaking, requires large quantities of water as well. Conversely, water usage requires large amounts of energy. Water is needed to cool thermoelectric power plants—coal, nuclear, gas, or concentrated solar thermal—and extract fossil fuels from the ground. Energy is needed for water treatment and distribution to agricultural, industrial, and residential customers. The full interdependence is a complicated one, often with a compounding effect. For example, as more people move to the West, more electricity is needed. And higher temperatures brought on by climate change call for more air conditioning, which further amplifies the electrical demand. All this additional electricity requires additional water to cool the power plants, even as climate and weather changes induce increasingly severe water shortages. In turn, pumping and treating the additional water requires still more energy. The bottom line is this: any strain on either resource, water or energy, produces a corresponding strain on the other.

Naturally, this "water-energy nexus" has garnered the attention of the federal government, notably the Department of Energy (DOE), partly because water scarcity and variability could introduce vulnerabilities in the U.S. energy system. The DOE published a major report in the past year highlighting challenges associated with the water-energy nexus, identifying key efforts needed in technology, and addressing vulnerabilities and potential adaptation strategies. Taking on these challenges would require a partnership between the DOE and a broad range of external partners, including all levels of government, private-sector companies, academic institutions, and nongovernment organizations, as well as internal partners, the national laboratories. Los Alamos, for its part, has key modeling capabilities to predict and quantify various aspects of the water-energy nexus and valuable expertise in related areas such as drought ecology and wildfire modeling.

Colorado case study

In the early 2000s, before the current U.S. boom in natural gas and oil production was ushered in by horizontal drilling and hydraulic fracturing technologies, the DOE recognized that achieving energy independence might require developing harder-to-get resources. Their attention at the time was drawn to the Piceance Basin in northwestern Colorado, part of the Upper Colorado River Basin and home to one of the world's richest known oil-shale deposits.

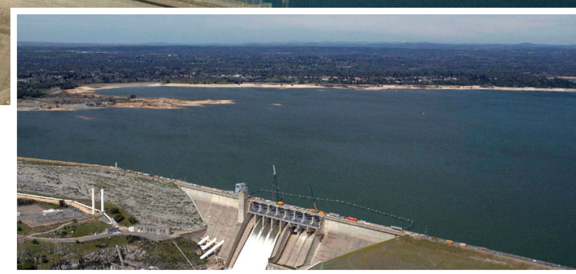
Oil shale is a type of rock that contains a mixture of organic chemicals called kerogen that can be converted into a liquid transportation fuel—a viable substitute for crude oil. But unlike crude oil, which can be directly extracted from underground reservoirs, this kerogen-rich fuel must first be separated from the rock before it can be extracted with conventional production wells. In their quest to investigate the efficacy of developing this potential resource, Shell Oil proposed a process of freezing enormous portions of the subsurface to isolate the oil recovery zone (to prevent groundwater contamination) and then heating the shale for several years to liberate its kerogen. Both the freezing and the heating would be extremely energy intensive, however, requiring significant additional electrical power production in the region. And that additional power production would likely place a prohibitive water and carbon premium on any transportation fuel produced.

The DOE originally asked Los Alamos to evaluate the water and carbon impacts of oil-shale development in the Piceance Basin. Although interest in oil shale soon waned at the DOE and in industry, the study provided an important opportunity to investigate the water impacts and requirements for increased thermoelectric power production in the region for any kind of development.

The Los Alamos research team, led by Andrew Wolfsberg, set out to investigate this representative nexus issue by assessing whether the river basin could provide a sufficient, reliable water supply under a variety of energy-production demands. Each such demand was characterized

Part of the Piceance Basin of northwestern Colorado. The Colorado River, Interstate 70, and many oil and gas sites can be seen.

CREDIT: EcoFlight



The Folsom Lake hydroelectric facility northeast of Sacramento was under severe drought at 17 percent of the lake's capacity in early 2014. (Inset: full capacity)
CREDIT: California Department of Water Resources

by its required daily water flow, which was assumed to be drawn from a hypothetical new water storage facility supplied by flows upstream of the Colorado-Utah border. The researchers would specify the size of the storage facility and simulate realistic river flows into it by taking into account the mountain precipitation that aggregates into a complex system of streams, river stretches, and existing reservoirs before reaching the new storage facility. They would then identify the maximum acceptable rate of withdrawal to prevent the new storage facility from dropping to useless levels (a "dead pool") during times of drought. By varying demands from different types of power production and introducing potential levels of climate change-induced variability, they could determine how much new water storage would be needed to accommodate each level of water use, even through a drought, under realistic flow conditions.

The river water supply to the reservoir was generated by a general hydrology model capable of analyzing the impacts of climate change on water availability and then calculating how much water could be safely removed for new energy development. The model spans the Colorado, Gunnison, and White Rivers, which form a complex system that currently includes nearly 800 man-made diversions, all calibrated to decades of input data from 89 weather stations, 105 stream gauges, and 18 reservior levels. The modeled rivers then experience diminished flows as a result of climate warming: less snowfall, earlier snowmelt, and greater evapotranspiration of rainfall (evaporation from land and transpiration through plants).

Would the water supply be adequate to support additional thermoelectric power production? To find out, Wolfsberg's team examined the simulated river flow and storage requirements near the Colorado-Utah border under a range of climate-change scenarios. The team found that a scenario with a 1°C rise in global temperatures throughout the study period would result in about 8 percent less cumulative river flow over the next 20 years, assuming all other conditions remain similar to the past. With a 2°C rise, the drop would be 16 percent. And the most extreme (but still plausible) climate-change scenario the team considered would produce a 25 percent cumulative reduction in river flow over 20 years.

"The remarkable thing we found is that, even for the same total amount of annual precipitation, the snowpack quantity, its minimum elevation, and the timing of its melt have a tremendous impact on how much flow makes it to the streams and reservoirs, and when," says Wolfsberg. "This, in turn, dramatically affects the availability of water for diversion at the times that it is needed."

Water use for power plant cooling depends on the type of power production and the technology invoked for cooling. Nuclear uses more than coal. Coal uses more than natural gas. And any type of fossil-fuel power plant will need more water with carbon capture and storage operations (CCS) than without. The researchers developed models of these differences to determine the size of the reservoir necessary to reliably supply the cooling water.

Andrew Wolfsberg

For example, if substantial electrical power production were added to the Upper Colorado region to meet growing energy demand in the West, say 4 gigawatts, then 50,000 acre-feet of additional water storage capacity should be sufficient for most types of power plant under current climate conditions. However, under a warmer future climate, the model projections indicate that significantly more storage would be needed for all types of power production other than natural gas combined-cycle technology and for any power production that includes CCS. The models make it easy to make such reevaluations with different assumptions about the power plant demands.

Aim for the best…

The Upper Colorado River Basin aside, the global population is growing and demanding more water and more energy. Meanwhile, climate change is exacerbating both the water shortfall and the energy demand. With these underlying causes decades or more away from abating, the water-energy nexus will only get more intense over time—that is, unless humanity can develop new technologies to reduce the amount of water spent on energy and vice versa. Indeed, the DOE and others are working on a number of promising technologies to help relieve the combined resource pressure.

A particularly important area for improved water-use efficiency is power plant cooling. The maximum efficiency of a thermoelectric power plant depends on two things. The first is the plant's high temperature, achieved by burning coal, for example, and used to convert water into high-energy steam and blow it through a turbine to generate electricity. The second is its low temperature, which is needed to condense the energy-spent steam back into water so that it can be pumped into the process anew.

In a world without water-use concerns, the easiest way to minimize the low temperature (and thereby maximize efficiency) is to divert surface freshwater from a nearby lake or river into the power plant. Heat from the plant is then transferred into this water, either by converting it to steam and allowing it to vent through the cooling towers or by sending it back into the lake or river. Neither option is suitable for a world with water-use concerns, however, since surface freshwater is either lost to the atmosphere as steam or returned to the lake or river at high temperature, causing significant ecological damage.

Fortunately, there are several ways to improve this approach to power plant cooling. For instance, certain substitutes for the standard water-steam power cycles produce less waste heat and therefore require less cooling. Alternatively, the waste heat emerging from the turbines could be put to use somehow, as in a heating system for a nearby industrial process, rather than expending it on vaporizing surface freshwater while the nearby industry gets its heat from the plant's electricity. The power plants could also install airflow-based cooling systems, or hybrid air and water cooling systems, instead of using only water.

In addition, the potential for energy-related water savings is not limited to electrical power plants. Hydraulic fracturing for fossil-fuel extraction, in which pressurized water is injected to fracture the rock and create a pathway for the oil or gas to get to the well bore, may be possible

Standard thermoelectric power plants, like this coal-fired plant in the United Kingdom, use freshwater for cooling to obtain a large temperature difference (between fuel-heated and cooled states) and correspondingly high efficiency. The heat transfers out of the plant and into the cooling water, producing steam. Much of the steam is recaptured for further use, but some is not and simply vents to the atmosphere. In this way, surface freshwater ceases to be available. (The vented steam may subsequently fall as rain, but that rain may fall over the ocean or may fall in a brief drizzle that produces no available surface water.)

Due to drought conditions, Lake Mead, the reservoir created by the Hoover Dam on the Colorado River, is currently less than half full and is on track to produce only about half of its designed hydroelectric generating capacity by 2016.

with highly brackish water from deep underground aquifers, or with other fluids, instead of freshwater—something Los Alamos is also investigating. And water-use efficiency can be improved in other areas, such as industrial processes, algal biofuel production, and carbon capture and storage.

Likewise, new technologies offer the potential for substantial energy savings in water processing. There are several systems under development, for example, to more efficiently process municipal wastewater. Once treated, municipal wastewater can be used for power plant cooling, as is the current cooling paradigm at the nation's largest power plant, the Palo Verde nuclear generating station outside of Phoenix. In addition, a number of efficiency-improving technologies are being explored for desalination, which could increase the freshwater supply from seawater and from brackish-water aquifers. Better yet, desalination plants could potentially be powered by the waste heat from power plants. These improvements and others are currently at various stages of development.

… but prepare for the worst

Meanwhile, Richard Middleton, a member of Wolfsberg's team at Los Alamos, is taking a new direction on the Piceance Basin research with a study of America's at-risk watersheds. In particular, he is interested in identifying how and when human use and climate change might push them past some "point of no return" and what we can do about it—critical information for policymakers.

"This is a serious energy and national security problem," says Middleton. "Many of our critical watersheds are already under severe stress. Then add projected changes in temperature, extremes of precipitation and drought, insect infestations, and climate-induced wildfires, and ask: Where are the tipping points that will disrupt our national water supplies for the long term?"

Middleton's research is designed to predict those tipping points and quantify the resulting changes in water supply and water quality, corresponding energy-resource impacts, and any other downstream effects. It leverages key model- and experiment-driven Los Alamos research, including how and why trees die; how and why wildfire spreads and what it does to watersheds; and advanced watershed-scale simulation to couple surface and subsurface water systems, accounting for climate change, vegetation dynamics, and complex feedbacks. By merging such components, Middleton is developing a new framework to reveal the tipping-point vulnerabilities and assess the effectiveness of various possible interventions, such as controlled burns or changes in aquifer management. If there's any combination of actions that will be particularly effective in protecting our coupled water and energy resources, he reasons, it's best to find out now.

"Obviously there are tough times ahead," he says. "And our best defense right now is knowledge—so we know what we're facing and how to focus our efforts." LDRD

—Craig Tyler